

# **MODELING OF PHOTOVOLTAIC ARRAY**

A PROJECT SUBMITTED IN PARTIAL FULFILLMENT  
OF THE REQUIREMENT FOR THE DEGREE OF

Bachelor of Technology  
in  
Electrical Engineering  
By

**Sushen Narkhede (10602004)**

**Rajpritam(10602057)**



**Department of Electrical Engineering**

**National Institute of Technology**

**Rourkela-769008, Orissa**

# **MODELING OF PHOTOVOLTAIC ARRAY**

A PROJECT SUBMITTED IN PARTIAL FULFILLMENT  
OF THE REQUIREMENT FOR THE DEGREE OF

Bachelor of Technology  
in  
Electrical Engineering  
By

**Sushen Narkhede (10602004)**

**Rajpritam(10602057)**

Under the guidance of

**Prof. SUSOVON SAMANTA**



**Department of Electrical Engineering**

**National Institute of Technology**

**Rourkela-769008, Orissa**

# ACKNOWLEDGEMENT

I would like to express my gratitude towards all the people who have contributed their precious time and effort to help me. Without whom it would not have been possible for me to understand and complete the project.

I would like to thank **Prof Susovon Samanta**, Department of Electrical Engineering, our Project Supervisor for his guidance, support, motivation and encouragement throughout the period this work was carried out. His readiness for consultation at all times, his educative comments, his concern and assistance even with practical things have been invaluable.

We are grateful to **Dr. B.D.Subudhi**, *Professor and Head*, Dept. of Electrical Engineering for providing necessary facilities in the department.

Sushen Narkhede(10602004)

Rajpritam(10602057)



**National Institute of Technology Rourkela**  
Rourkela-769008, Orissa

# **CERTIFICATE**

This is to certify that the Project entitled “**MODELING OF PVARRAY**” submitted by **Sushen Narkhede** and **Rajpritam** has in partial fulfillment of the requirements for the award of **Bachelor of Technology Degree in Electrical Engineering** at **National Institute of Technology, Rourkela** (Deemed University) is an authentic work carried out by them under my supervision and guidance.

Date:

(Prof. S.Samanta)

Place: Rourkela

Department of Electrical Engineering

NIT, Rourkela

# CONTENTS

ACKNOWLEDGMENT	3
CERTIFICATE	4
CONTENTS	5
LIST OF FIGURES	6
LIST OF TABLES	7
INTRODUCTION	8
ABSTRACT	9
Chapter 1: Preliminaries	10-12
1.1 Sun as a Source	
1.2 Solar energy reaching the earth's surface	
1.3 Spectrum of sun	
1.4 Normal Test Conditions	
Chapter 2: Photovoltaic Systems	13-18
2.1 Photovoltaic Groupings	
2.2 Working of a PV cell	
2.3 Characteristics of a PV cell	
2.4 Materials used in PV cell	
2.5 Photovoltaic Applications	
Chapter 3: Modeling of PV array	19-27
3.1 Representation of PV devices	
3.2 Improvisation of model	
3.3 Methods to determine the unknown parameters	
Chapter 4: Results	28-32
Chapter 5: Conclusion	33
Bibliography	34-35

## LIST OF FIGURES

Figure 1.1	Distribution of solar radiation	11
Figure 1.2	Spectral distributions of black body radiation and sun radiation	12
Figure2.1	Basic PV cell structure	13
Figure2.2	Photovoltaic Hierarchy	14
Figure2.3	Working of PV cell	15
Figure2.4	Characteristics of a PV cell	15
Figure3.1	Single Diode model	19
Figure3.2	Double Diode model	20
Figure4.1	<i>I-V curve obtained for SOLTECH 1STH-235</i>	29
Figure4.2	<i>P-V curve obtained for SOLTECH 1STH-235</i>	30
Figure4.3	<i>I-V curve of SOLTECH 1STH-235 at different temperatures</i>	30
Figure4.4	<i>P-V curve of SOLTECH 1STH-235 at different temperatures</i>	31
Figure4.5	<i>I-V curve of SOLTECH 1STH-235 at different Irradiations</i>	31
Figure4.6	<i>P-V curve of SOLTECH 1STH-235 at different Irradiations</i>	32

## LIST OF TABLES

Table 4.1: Showing known parameters given in datasheet ( <b>Manufacturer - Soltech</b> Model-1STH-235)	28
Table 4.2: Showing unknown parameters obtained from MATLAB simulation by first method.	28
Table 4.3: Showing unknown parameters obtained from MATLAB simulation by second method.	29

## **INTRODUCTION**

Photovoltaic's (PVs) are arrays (combination of cells) that contain a solar voltaic material that converts solar energy into electrical energy. PV cell is a basic device for Photovoltaic Systems. Such systems include multiple components like mechanical and electrical connections and mountings and various means of regulating and (if required) modifying the electrical output. Materials that are used for photovoltaic are mono-crystalline silicon, polycrystalline silicon, microcrystalline silicon, cadmium telluride and copper indium selenide. The current and voltage available at the PV device terminals can be directly used to feed small loads like lighting systems or small DC motors. In order to extract maximum amount of power from PV array we have to model converters so that it can track Maximum Power Point (MPP).



## **ABSTRACT**

Day-by-day the energy demand is increasing and thus the need for a renewable source that will not harm the environment are of prime importance. Some projections state that by 2050 the energy demand will triple. Yet majority of the energy requirements is satisfied by fossil fuels but by the use of photovoltaic systems could help in supplying the energy demands. In this project we have dealt with problem that persists with the modeling of photovoltaic device. The problem that various models of photovoltaic device face is the number of unknown parameters which are not mentioned in the datasheet. Various methods have been proposed in order to determine these unknown parameters. Basically, in this project, two of the proposed methods are being studied and then compared. This can give a brief idea to the manufacturers who design power electronics products about the easy-to-use modeling methods that can be used in simulation of photovoltaic arrays.

# CHAPTER-1

## PRELIMINARIES

### 1.1 Sun as a Source

The energy from the sun is supplied in the form of radiation. The energy is generated in the sun's core through the fusion of hydrogen atoms into helium. Now due to the larger distance of sun from the earth only a small portion of sun's radiation reaches earth's surface. The intensity of solar radiation reaching earth's surface is around 1369 watts per square metre [ $\frac{W}{m^2}$ ]. This is known as the solar constant. The total solar radiation intercepted by earth's surface can be calculated by multiplying solar constant with the cross section area of the earth. In order to calculate the solar radiation received, on average per square metre of earth's surface we divide the above multiplied result by the surface area of the earth. Thus the average solar radiation(S) per square metre of earth's surface is given by[E]

$$R = \frac{S*3.14*r^2}{4*3.14*r^2} = \frac{1369}{4} = \text{approx.}342\frac{W}{m^2} \quad (1)$$

Where S – solar constant in  $\frac{W}{m^2}$

r- Radius of earth

### 1.2 Solar energy reaching the earth's surface

Till now the effect of earth's atmosphere is not taken into consideration. The value calculated above is for the average solar radiation intensity at the outer regions of earth's atmosphere. So we are interested to know how much of this energy actually reaches the earth surface.

The atmosphere absorbs about  $68 \frac{W}{m^2}$  and reflects  $77 \frac{W}{m^2}$  (Wallace and Hobbs 1977). The radiation reaching the earth's surface is  $198 \frac{W}{m^2}$ . The intensity of solar radiation also depends on the time of the year and the geographical positions.

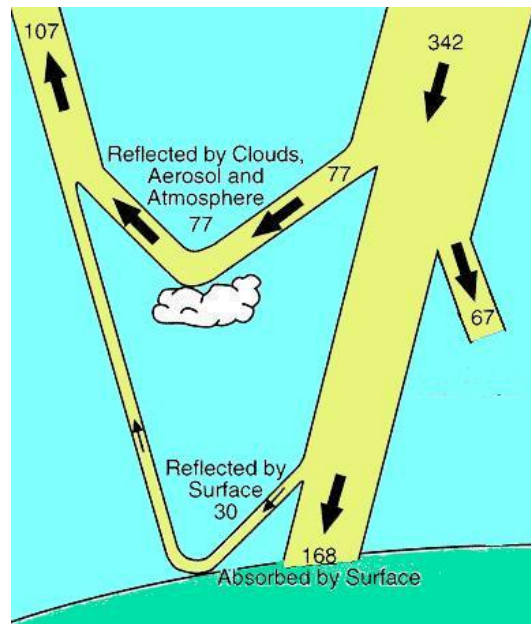


Figure 1.1: The distribution of solar radiation. [Source: Modified figure of Houghton et al. 2001][E]

From the figure above we can see that every square metre of the upper regions of the atmosphere receives  $342 \frac{W}{m^2}$ .  $67 \frac{W}{m^2}$  of energy is absorbed by the atmosphere and  $77 \frac{W}{m^2}$  is reflected. About  $198 \frac{W}{m^2}$  energy reaches the earth's surface of which  $30 \frac{W}{m^2}$  is reflected back to space.

The intensity of solar radiation also depends on the time of the year and geographical positions as illustrated in figure 2.

The energy that reaches the earth surface is around 3.2 EJ/y. If we are able to harvest even a small fraction of the available energy at the earth surface we could solve our energy problems. The energy reaching the earth surface is around 7000times the global energy consumptions. But the global solar energy consumptions in 2005 was only 0.014% of the total solar energy reaching the earth surface.

### 1.3 Spectrum of sun

The efficiency of a PV device is dependent on the spectral distribution of solar radiation. The evaluation of PV devices is generally done with reference to a standard spectral distribution. There are two standard terrestrial distribution defined by the American Society for Testing and Materials (ASTM), direct normal and global AM1.5. The direct normal standard corresponds to the solar radiation that is perpendicular to a plane directly facing the sun. The global corresponds to the spectrum of the diffuse radiations. Radiations which are reflected on earth's surface or influenced by atmospheric conditions are called diffuse radiations. To measure the global radiations an instrument named pyranometer is used. This instrument is

designed in such a way that it responds to every wavelengths and so that we get an accurate value for total power in any incident spectrum.

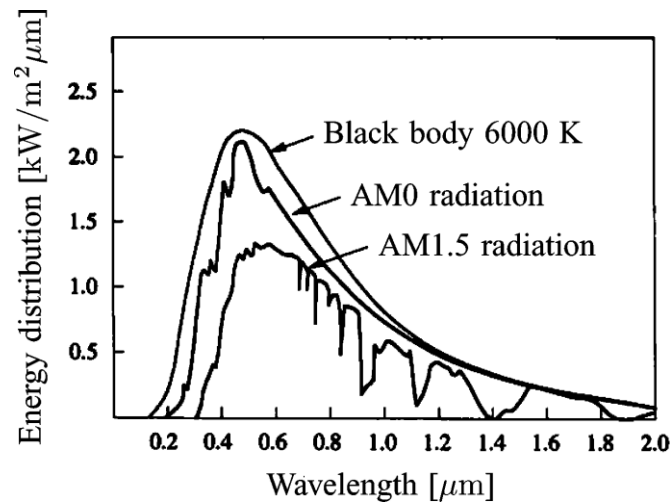


Figure1.2: Spectral distribution of black body radiation and sun radiation. Source: Moller [2]

The AM initials in the figure above stands for air mass. The air mass in this context means the mass of air between a surface and the sun [11]. The length of the path of solar radiation from the sun through the atmosphere is indicated by the number AMx. The longer the path the more is the deviation of light.

#### 1.4Nominal Test Conditions

Usually we specify standard conditions. This is done so that a comparison on the basis of performance between different PV cells can be done. The parameters are generally given in a datasheet. The datasheets provide remarkable parameters regarding the performance and characteristics of PV arrays with respect to these standard test conditions.

The nominal (standard) test conditions are as follows:

$$\text{Irradiance } (G_n) = 1000 \frac{W}{m^2}$$

$$\text{Temperature } (T_n) = 25 \text{ } ^\circ\text{C}$$

$$\text{Spectrum of } x = 1.5 \text{ i.e., AM1.5 [12].}$$

## CHAPTER-2

### PHOTOVOLTAIC SYSTEMS

French physicist, Edmund Bequerel, was the one to note the photoelectric effect back in 1839. He found that certain materials have property to produce small amounts of electric current when exposed to sunlight. In 1905, Albert Einstein described the nature of light and the photoelectric effect which has become the basic principle for photovoltaic technology. The first photovoltaic module was built by Bell Laboratories in 1954[M].

#### 2.1 Photovoltaic Groupings

##### 3.1.1 Photovoltaic cell

PV cell are basically semiconductor diode. This semiconductor diode has got a p-n junction which is exposed to light. When illuminated by sunlight it generates electric power [1], [2]. PV cell are made up of various semiconductor materials. But mono-crystalline silicon and poly-crystalline silicon are mainly used for commercial use.

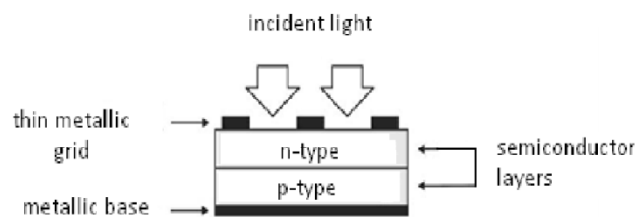


Figure.2.1: Basic PV cell structure [18]

##### 2.1.2 Photovoltaic module

The power produced by a single PV cell is not enough for general use. So by connecting many single PV cell in series (for high voltage requirement) and in parallel (for high current requirement) can get us the desired power. Generally a series connection is chosen this set of arrangement is known as a module. Generally commercial modules consist of 36 or 72 cells. The modules consist of transparent front side, encapsulated PV cell and back side. The front side material is usually made up of low-iron and tempered glass. The efficiency of a PV module is less than a PV cell. This is due to the fact that some radiation is reflected by the glass cover and frame shadowing etc.

### 2.1.3 Photovoltaic Array

A photovoltaic array (PV system) is a interconnection of modules which in turn is made up of many PV cells in series or parallel. The power produced by a single module is seldom enough for commercial use, so modules are connected to form array to supply the load. The connection of the modules in an array is same as that of cells in a module. Modules can also be connected in series to get an increased voltage or in parallel to get an increased current. In urban uses, generally the arrays are mounted on a rooftop. In agricultural use, the output of an array can directly feed a DC motor.

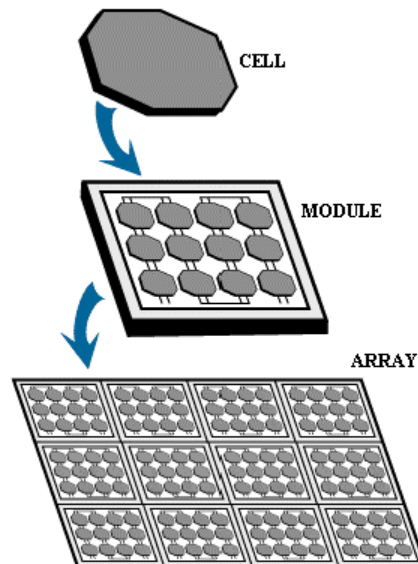


Figure2.2: Photovoltaic Hierarchy [M]

## 2.2 Working of PV cell

Working of a PV cell is based on the basic principle of photoelectric effect. Photoelectric effect can be defined as a phenomenon in which an electron gets ejected from the conduction band as a consequence of the absorption of sunlight of a certain wavelength by the matter(metallic or non-metallic solids, liquids or gases).So, in a photovoltaic cell, when sunlight strikes its surface, some portion of the solar energy is absorbed in the semiconductor material. If absorbed energy is greater than the band gap energy of the semiconductor, the electron from valence band jumps to the conduction band. By this, pairs of hole-electrons are created in the illuminated region of the semiconductor. The electrons thus created in the conduction band are now free to move. These free electrons are forced to move in a particular

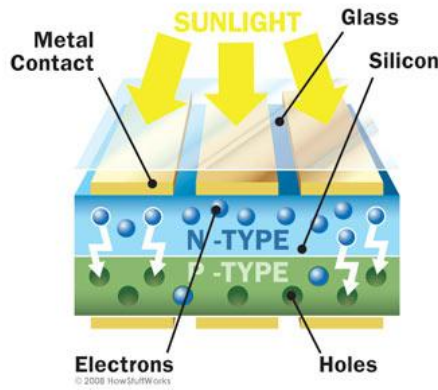


Figure2.3: Working of PV cell [E]

direction by the action of electric field present in the PV cells. These flowing electrons constitutes current and can be drawn for external use by connecting a metal plate on top and bottom of PV cell. This current and the voltage (created because of its built-in electric fields) produces required power.

### 2.3 Characteristics of a PV cell

In a PV characteristic there are basically three important points viz. open circuit voltage ( $V_o$ ), short circuit current ( $I_s$ ) and maximum power point ( $I_{mpp}, V_{mpp}$ ). The maximum power that can be extracted from a PV cell are at the maximum power points. Usually manufacturers provide these parameters in their datasheets for a particular PV cell or module. By using these parameters we can build a simple model but for more information is required for designing an accurate model.

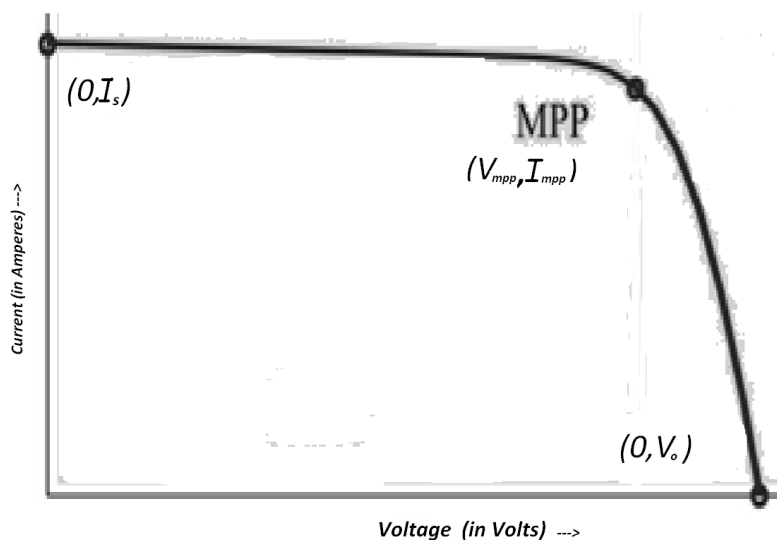


Figure2.4: characteristics of a PV cell

The characteristic Equation for the PV cell is given by:

$$I = I_{ph} - I_{0s} \left[ \exp \left( \frac{V + R_{se}I}{V_t a} \right) - 1 \right] - \frac{V + R_{se}I}{R_{pa}} \quad (2)$$

Where,

$I_{ph}$  - Light-generated Current or Photocurrent: It is generated directly by incident of sunlight on the PV cell. This current varies linearly with sun irradiation and depends on temperature given by [18]:

$$I_{ph} = (I_{ph,n} + K_i \Delta T) \frac{G}{G_n} \quad (3)$$

where,  $I_{ph,n}$  = Light-generated current at nominal condition

$K_i$  = Current temperature co-efficient (in)

$G$  = Actual sun irradiation (in  $\frac{W}{m^2}$ )

$G_n$  = Nominal sun irradiation

$\Delta T$  = It is the difference between actual temperature and nominal temperature (in Kelvin) i.e.,  $(T - T_n)$

$I_{0s}$  - Diode Saturation Current: It is a part of the reverse current in a diode caused by diffusion of minority carriers from the neutral regions to the depletion region.

$R_{se}$  &  $R_{pa}$  — Due to the presence of internal resistances, the power loss takes place in the cell. These parasitic resistances can be segregated into *series resistance*,  $R_{se}$  and *parallel resistance*,  $R_{pa}$ . For ideal case,  $R_{se}$  would be ‘zero’ and  $R_{pa}$  would be ‘infinity’.

$a$  — Diode ideality factor: It is the measure of how much a practical diode deviates from ideal diode equation. The average value assumed during the determination of unknown parameters in the photovoltaic system is usually ‘1.3’.



$V_t$  — Junction thermal voltage: It is a characteristic voltage that relates current flow in the p-n junction to the electrostatic potential across it.

$$V_t = kT/q;$$

Where,

$k$  = Boltzmann constant =  $1.3806503 \times 10^{-23}$  J/K

$q$  = electron charge =  $1.607 \times 10^{-19}$  C

$T$  = Nominal Temperature = 298.15 K

## 2.4 Materials used in PV cell

As mentioned above the materials used in PV cells are described below.

- Mono-crystalline Silicon

Earlier mono-crystalline silicon has been extensively used in the making of PV cells but nowadays polycrystalline silicon has replaced it. Mono-crystalline Silicon was in use just because of its stability and desirable chemical and physical properties of silicon.

- Polycrystalline Silicon

This material has surpassed mono-crystalline silicon because it is cheaper. The cost of silicon comprises of a major portion of the total cost of a cell. The manufacturing cost of poly-crystalline silicon is less. This results in cheaper cells.

- Micro-crystalline Silicon

Micro-crystalline also known as nano-crystalline is a form of porous silicon. It is an allotropic form of silicon with para-crystalline structure. Nano-crystalline differs from poly-crystalline in a way that the former contains small grains of crystalline silicon within the amorphous phase whereas poly-crystalline consists solely of silicon crystalline grains. The factor that differentiates poly-crystalline and micro-crystalline silicon is the grain size. It has got several advantages over mono-crystalline and poly-crystalline. It has got increased stability and also it is easier to fabricate.

- Cadmium Telluride (CdTe)

It is a crystalline compound formed from cadmium and tellurium. In the formation of p-n junction photovoltaic solar cell cadmium telluride is usually sandwiched with cadmium sulfide.

- Copper Indium Selenide

It is a compound semi conductor material. It is composed of copper, indium and selenium. The material is a solid solution of copper indium selenide. Unlike amorphous silicon, light-induced degradation does not take place in CIS solar cells.

## **2.5 Photovoltaic Applications**

Photovoltaic systems are used in variety of applications. Stand alone system is a good application of PV systems. A stand alone system does not have a utility connection. It uses power as it is produced.

- **Lighting:** The availability of low pressure sodium and fluorescent lights that runs on low power DC has made PV systems an ideal source for lighting in remote places. PV systems are used to provide lighting for street lights, information signs, parking lots and homes.
- **Communications systems:** PV systems are used in transmitters, cellular phones, portable computers, satellites, mobile radio systems etc.
- **Informative signs:** Some devices like highway warning alarms, railroad signs, navigational beacons, aircraft beacons can't be connected to utility grids. PV systems are used for these kinds of applications.
- **Water Pumps:** PV output can be directly fed to DC pumps. These pumps can be directly operated to provide water for irrigation, village water supply or for livestock.
- **Vehicles:** Solar power can be use to charge vehicle batteries.
- **Refrigeration:** PV systems are used for storage of medicines in remote places.
- **General use:** Solar power is used in watches, calculators, lanterns, fans, radios and outdoor lights.

## CHAPTER-3

### MODELING OF PV ARRAY

Modeling of PV modules or arrays is required in order to design and monitor these systems. Usually, a Grey Model process is used to model PV arrays. In such models, physical parameters are determined using the measured data given in the datasheets (by manufacturers).

In this chapter, we will explain the basic models of PV array and their advantages and disadvantages over one another. Then, we will go through the two methods to determine the unknown parameters using known ones and their comparison.

#### 3.1 Representation of PV devices

The PV devices are basically represented in two different models viz.

- Single diode model
- Double diode model

##### 3.1.1 Single diode model

In a single diode model, there is a current source parallel to a diode. The current source represents light-generated current,  $I_{ph}$  that varies linearly with solar irradiation. This is the simplest and most widely used model as it offers a good compromise between simplicity and accuracy [18],[20]. Figure below shows the single diode model circuit.

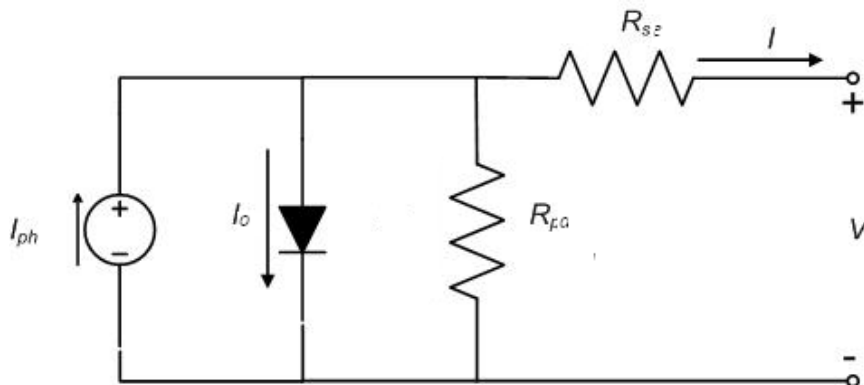


Figure3.1: Single diode model [21]

The characteristic equation for single diode model is given by [21]:

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{V + R_{se}I}{V_t a} \right) - 1 \right] - \frac{V + R_{se}I}{R_{pa}} \quad (4)$$

### 3.1.2 Double diode model

In this model an extra diode attached in parallel to the circuit of single diode model. This diode is included to provide an even more accurate I-V characteristic curve that considers for the difference in flow of current at low current values due to charge recombination in the semiconductor's depletion region [22].

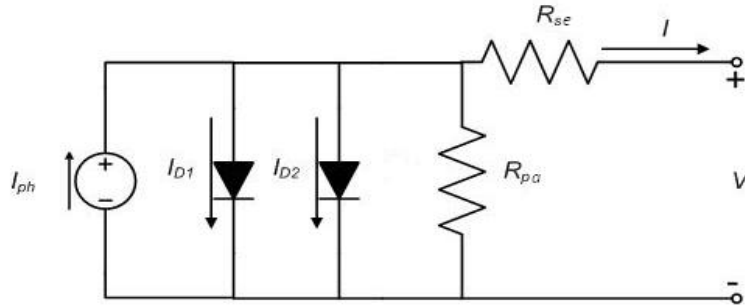


Figure3.2: Double Diode Model [21]

The accuracy of this model more than the single diode model but because of the difficulty to solve the equation, single diode model is preferred.

The characteristic equation for double diode model is given by [21]:

$$I = I_{ph} - I_{o1} \left\{ \exp \left[ \frac{(V + IR_{se})}{V_t} \right] - 1 \right\} - I_{o2} \left\{ \exp \left[ \frac{(V + IR_{se})}{aV_t} \right] - 1 \right\} - \frac{V + IR_{se}}{R_{pa}} \quad (15)$$

Where,

$I_{o1}$  - Saturation current due to diffusion

$I_{o2}$  - Saturation current due to recombination in the space charge layer

(Note: All other parameters are explained in previous chapter.)

For simplicity, single diode model is studied in this project.

### 3.2 Improvisation of Model

The Diode saturation current,  $I_{0s}$  can be expressed by [18], [23]:

$$I_{os} = I_{os,n} \left( \frac{T_n}{T} \right)^3 \exp \left[ \frac{qE_g}{ak} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right] \quad (6)$$

Where,  $E_g$  is band gap energy of semiconductor ( $E_g = 1.12$  eV for the polycrystalline Si at 25 °C [18], [23], [24])

And  $I_{os,n}$  is diode saturation current at nominal test conditions given by [18]:

$$I_{os,n} = \frac{I_{sn}}{\exp \left( \frac{V_{on}}{aV_{tn}} \right) - 1} \quad (7)$$

Where,

$I_{sn}$ ,  $V_{on}$  and  $V_{tn}$  are short-circuit current, open circuit voltage and junction thermal voltage at nominal conditions respectively.

Now, the single diode model of PV device can be improved by modifying the above equation by [18]:

$$I_{os,n} = \frac{(I_{sn} + K_i \Delta T)}{\exp \left[ \left( \frac{V_{on} + K_v \Delta T}{aV_{tn}} \right) \right] - 1} \quad (8)$$

Since, the saturation current has strong temperature dependence; equation (8) results in a linear variation of  $I_{os,n}$  with respect to temperature,  $T$ . The model's validity with the new equation has been tested experimentally [18].

### 3.3 Methods to determine the unknown parameters

As mentioned earlier, we have considered two methods for determining the unknown parameters using the known ones (from the datasheet).

There are five unknown parameters in the characteristic equation (5) of a single diode model which are,  $(I_{ph}, I_{os}, a, R_{se}, R_{pa})$

In this part of the chapter the two methods are explained one by one and then are compared in the forthcoming chapter.

#### 3.3.1 First Method (Using Newton's Method)

In this method, we assume diode ideality factor,  $a=1.3$ .

Now, we remain with four unknown parameters  $(I_{ph}, I_{os}, R_{se}, R_{pa})$ .

$I_{os}$  can be calculated using equation (7)

It is trivial that there can be only one pair of  $(R_{se}, R_{pa})$  that warranties

$P_{max,m} = P_{max,e}$  at maximum power-point condition.

From [18], the relationship can be found between  $R_{se}$  and  $R_{pa}$  by making

$P_{max,m} = P_{max,e}$  as shown.

$$P_{max,m} = V_{mpp} \left\{ I_{ph} - I_{os} \left[ \exp \left( \frac{V_{mpp} + R_{se} I_{mpp}}{a V_t N_s} \right) - 1 \right] - \frac{V_{mpp} + R_{se} I_{mpp}}{R_{pa}} \right\} = P_{max,e} \quad (9)$$

$$R_{pa} = \frac{V_{mpp} (V_{mpp} + R_{se} I_{mpp})}{\left\{ V_{mpp} I_{ph} - V_{mpp} I_{os} \left[ \left( \frac{V_{mpp} + R_{se} I_{mpp}}{a V_t N_s} \right) \right] + V_{mpp} I_{os} - P_{max,e} \right\}} \quad (10)$$

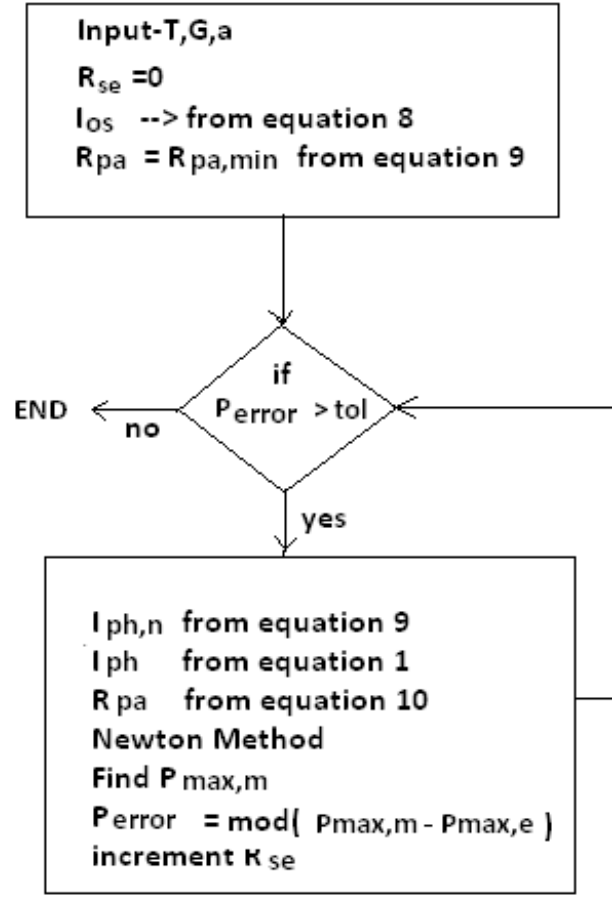
In order to find out  $R_{se}$  and  $R_{pa}$ , we need to do certain number of iterations so that the peak value of power at maximum power-point,  $P_{max,m}$  equals experimental MPP power,  $P_{max,e}$ . It can be easily done using a numerical method. It is required to choose proper initial conditions for these unknown parameters.  $R_{se}$  can be initialized by 0 and then slowly incremented. As mentioned earlier, parallel resistance can be approximated to the inverse of slope at  $I_s$ . So, we can easily assume the initial condition for  $R_{pa}$  to be the negated inverse of slope at  $I_s$ . Thus, we get

$$R_{pa,min} = \frac{V_{mpp}}{I_{s,n} - I_{mpp}} \quad (11)$$

Previously, for simplicity, authors used to assume  $I_{sn} = I_{phn}$ . but since due to iterative updates  $R_{se}$  and  $R_{pa}$ , the model developed can be further improved by [18]

$$I_{ph,n} = \frac{R_{pa} + R_{se}}{R_{pa}} I_{s,n} \quad (12)$$

Following figure shows the algorithm that can be followed using MATLAB in order to unknown parameters.



### 3.3.2 Second Method (using Newton-Raphson method to solve system of non-linear equations)

Since, there are five unknown parameters, if we are able to get five equations in terms of these unknowns, they can be solved easily to get the solution [21].

There are three remarkable points on the I,V curve. These are at short-circuit condition, open-circuit condition and maximum power-point condition.

At short circuit condition,  $I = I_s$  and  $V = 0$ . After substituting these values in equation (5), we obtain

$$I_{ph} = I_{os} \left\{ \exp \left[ \frac{V_0}{aV_t} \right] - 1 \right\} - \frac{V_0}{R_{pa}} \quad (13)$$

Similarly, for Open-circuit condition ( $I = 0$  and  $V = V_0$ ), we obtain



$$I_s = I_{ph} - I_{0s} \left\{ \exp \left[ \frac{I_s R_{se}}{a V_t} \right] - 1 \right\} - \frac{I_s R_{se}}{R_{pa}} \quad (14)$$

And for Maximum power-point condition ( $I = I_{mpp}$  and  $V = V_{mpp}$ ), we obtain

$$I_{mpp} = I_{ph} - I_{0s} \left\{ \exp \left[ \frac{V_{mpp} + R_{se} I_{mpp}}{a V_t} \right] - 1 \right\} - \frac{V_{mpp} + R_{se} I_{mpp}}{R_{pa}} \quad (15)$$

These three equations are obtained using these key points.

In order to get another two equations, we can differentiate equation (5) with respect to  $V$ . Thus, we get

$$\frac{dI}{dV} = -I_{0s} \left\{ \frac{1}{V_t} \left( 1 + \frac{dI}{dV} R_{se} \right) \exp \left[ \frac{V + I R_{se}}{a V_t} \right] \right\} - \frac{1}{R_{pa}} \left( 1 + \frac{dI}{dV} R_{se} \right) \quad (16)$$

Again, by substituting short-circuit condition in equation (16), we obtain,

$$\left. \frac{dI}{dV} \right|_{V=0} = -I_{0s} \left\{ \frac{1}{V_t} \left( 1 + \left. \frac{dI}{dV} \right|_{V=0} R_{se} \right) \exp \left[ \frac{I_s R_{se}}{a V_t} \right] \right\} - \frac{1}{R_{pa}} \left( 1 + \left. \frac{dI}{dV} \right|_{V=0} R_{se} \right) \quad (17)$$

Again, by substituting open-circuit condition in equation (17), we obtain,

$$\left. \frac{dI}{dV} \right|_{I=0} = -I_{0s} \left\{ \frac{1}{V_t} \left( 1 + \left. \frac{dI}{dV} \right|_{I=0} R_{se} \right) \exp \left[ \frac{V_0}{a V_t} \right] \right\} - \frac{1}{R_{pa}} \left( 1 + \left. \frac{dI}{dV} \right|_{I=0} R_{se} \right) \quad (18)$$

The power transferred from the PV device is given by

$$P = IV \quad (19)$$

This differentiating power equation (19) with respect to  $V$ , we get

$$\frac{dP}{dV} = I + V \frac{dI}{dV} \quad (20)$$

To find the value at value of power at maximum power point we need to equate

$$\frac{dP}{dV} = 0$$

Substituting  $\frac{dI}{dV} = -\frac{I_{mpp}}{V_{mpp}}$ , we get following equation,

$$\frac{I_{mpp}}{V_{mpp}} = -I_{0s} \left\{ \frac{1}{V_t} \left( 1 - \frac{I_{mpp}}{V_{mpp}} R_{se} \right) \exp \left[ \frac{V_{mpp} + R_{se} I_{mpp}}{a V_t} \right] \right\} - \frac{1}{R_{pa}} \left[ 1 - \frac{I_{mpp}}{V_{mpp}} R_{se} \right] \quad (21)$$

Thus, the equations obtained in the preceding analysis are independent and can be easily solved in MATLAB using iterative method to solve system of non-linear equations like Newton-Raphson method.

For notational convenience, following can be defined,

$$R_{so} = \left. \frac{dV}{dI} \right|_{V=V_0} \quad (22)$$

$$R_{sho} = \left. \frac{dV}{dI} \right|_{I=I_s} \quad (23)$$

$R_{so}$  and  $R_{sho}$  can be obtained experimentally from the I-V curve[25].

Based on the work of [25], the initial can be calculated by calculating the diode ideality factor as follows[21]:

For diode ideality factor,

$$a = \frac{V_{mpp} + R_{so} I_{mpp} - V_0}{V_t \left\{ \ln \left( I_s - \frac{V_{mpp}}{R_{sho}} - I_{mpp} \right) - \ln \left( I_s - \frac{V_0}{R_{pa}} \right) + \frac{I_{mpp}}{I_s - \left( \frac{V_0}{R_{sho}} \right)} \right\}} \quad (24)$$

Then, the rest of the initial values can be determined as follows[21],[25]:

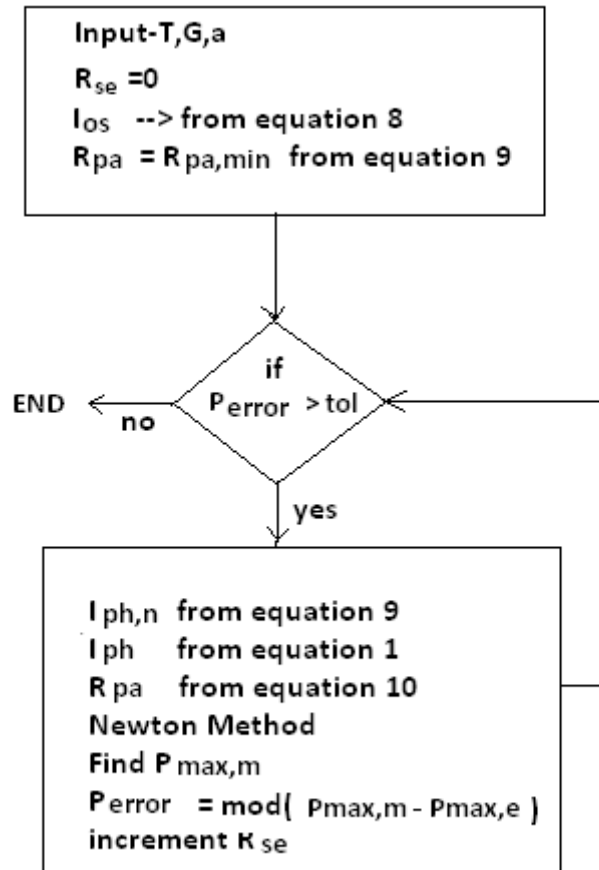
$$R_{pa} = R_{sho} \quad (25)$$

$$I_{os} = \left( I_s - \frac{V_0}{R_{pa}} \right) \exp \left( -\frac{V_0}{aV_t} \right) \quad (26)$$

$$R_{se} = R_{so} - \frac{aV_t}{I_{os}} \exp \left( -\frac{V_0}{aV_t} \right) \quad (27)$$

$$I_{ph} = I_s \left( 1 + \frac{R_{se}}{R_{pa}} \right) + I_{os} \left( \exp \frac{I_s R_{se}}{aV_t} - 1 \right) \quad (28)$$

Using Newton-Raphson method or other algorithm to solve system of non-linear equations and above initial values, a numerical solution can be obtained.



## CHAPTER 4

### RESULTS

The results we obtained are based on the “*SOLTECH 1STH-235*”.

Following table shows the both the known parameters(from the datasheet) and unknown parameters obtained from MATLAB simulation of first method.

Datasheet: **Manufacturer - Soltech** Model-1STH-235

Parameters	Values
$N_s$	60
$P_{max,e}$	235 W
$V_{mpp}$	29.3 V
$I_{mpp}$	8.03A
$V_o$	37.0V
$I_{sc}$	8.54A
$K_v$	-0.37 %/°C
$K_i$	+0.009 %/°C

Table 4.1: Showing known parameters given in datasheet (**Manufacturer - Soltech** Model-1STH-235)

The following table shows the unknown parameters obtained from MATLAB simulation by first method.

Parameters	Values
a	1.3
$R_{se}$	0.519 ohm
$R_{pa}$	431.77 ohm
$I_{os}$	3.85e – 13 A
$I_{ph}$	8.55 A

Table 4.2: Showing unknown parameters obtained from MATLAB simulation by first method.

Similarly by obtaining parameters from the datasheet given in table 4.1, following unknown parameters are obtained from MATLAB simulation by second method.

Parameters	Values
a	1.08
$R_{se}$	0.732 ohm
$R_{pa}$	-449.629 ohm
$I_{os}$	-2.12e-08 A
$I_{ph}$	8.547A
$R_{so}$	0.57 ohm
$R_{sho}$	450ohm

Table 4.3: Showing the unknown parameters are obtained from MATLAB simulation by second method.

Figure below shows the I-V curve and P-V curve that can be obtained.

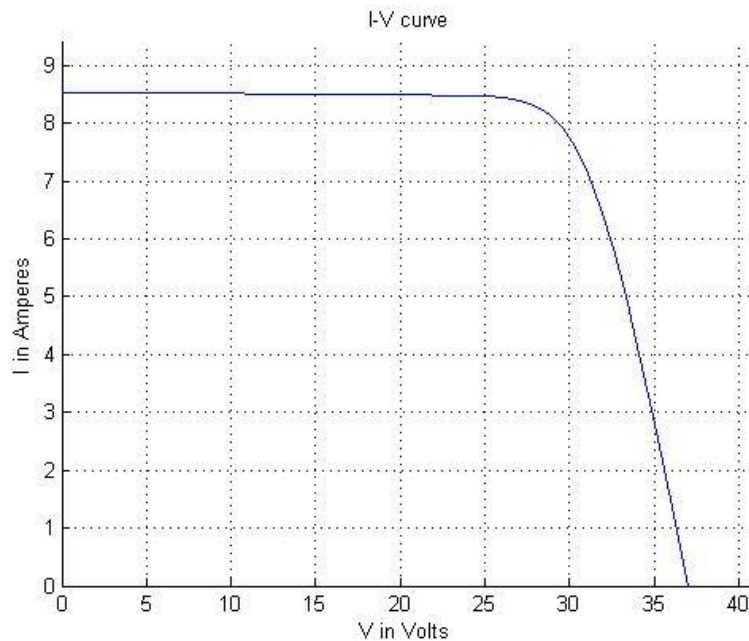


Figure (4.1) *I-V curve obtained for SOLTECH 1STH-235*

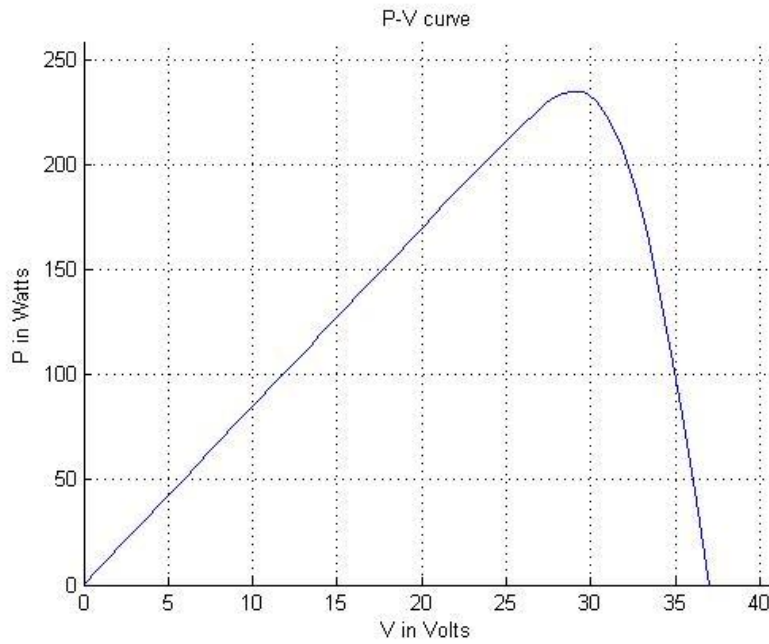


Figure (4.2) *P-V curve obtained for SOLTECH 1STH-235*

#### 4.2 Variation of characteristics with respect to Temperature

Following figure shows the change in I-V curve with temperature from 25°C to 45°C.

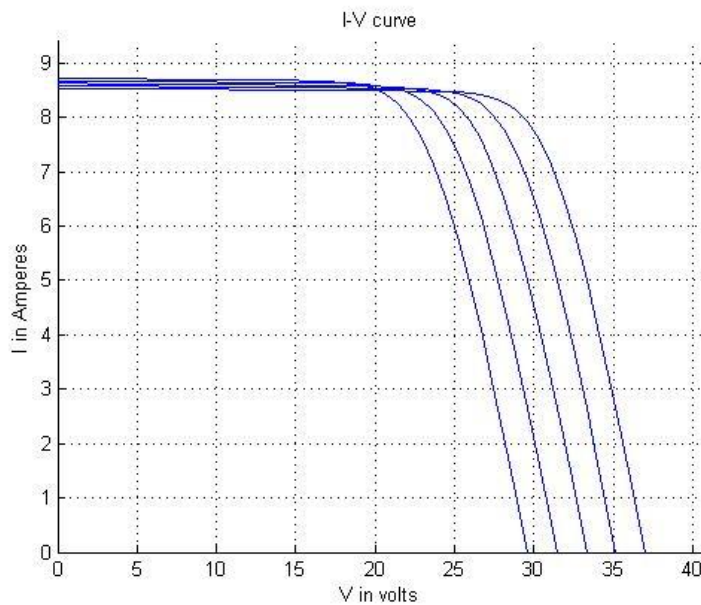


Figure (4.3) *I-V curve of SOLTECH 1STH-235 at different temperatures*

It can be observed from above figure that open-circuit voltage decreases with increase in temperature.

Following figure shows change in P-V curve with temperature from 25°C to 45°C.

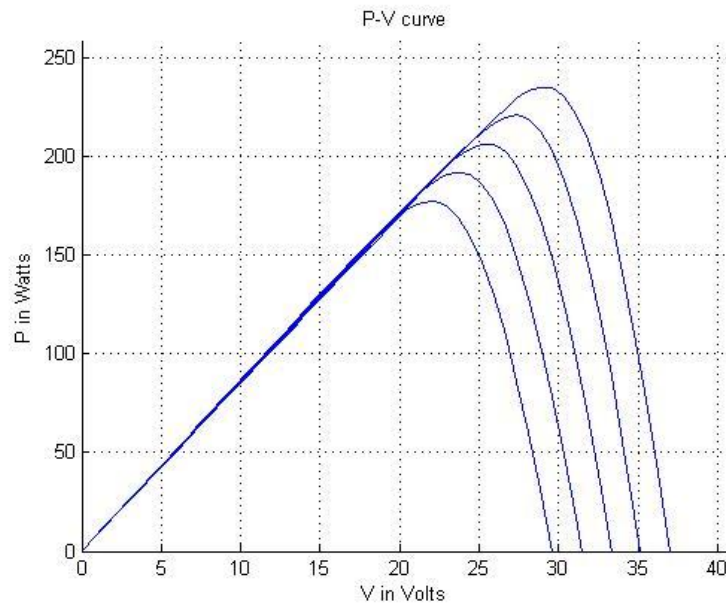


Figure (4.4) *P-V curve of SOLTECH 1STH-235 at different temperatures*

It is clear from the above figure that with the increase in temperature power at maximum power-point decreases.

#### 4.2 Variation of characteristics with respect to Irradiation

Following figure shows the variation of I-V characteristics with irradiation from  $400 \frac{W}{m^2}$  to  $1000 \frac{W}{m^2}$ .

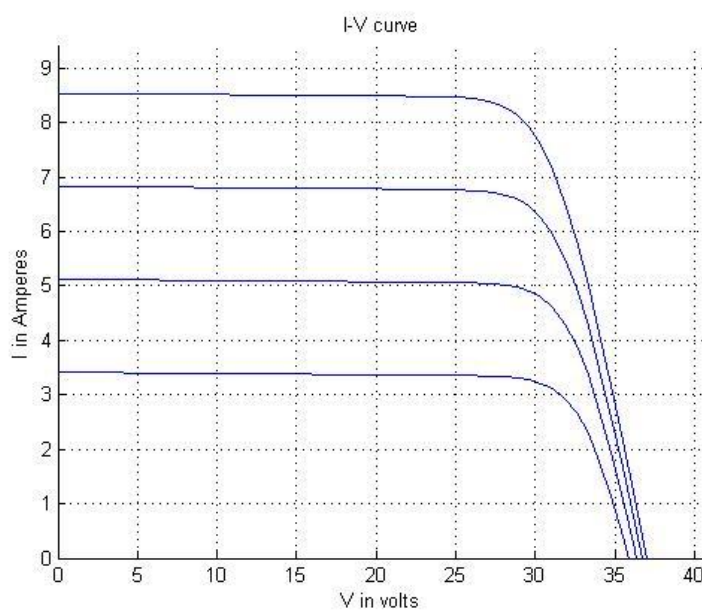


Figure (4.5) *I-V curve of SOLTECH 1STH-235 at different Irradiations*

It can be observed from the above figure that the short-circuit current decreases with decrease in irradiation which is obvious since, they possess linear relationship.

Following figure shows variation of P-V characteristic with irradiation from  $400 \frac{W}{m^2}$  to  $1000 \frac{W}{m^2}$ .

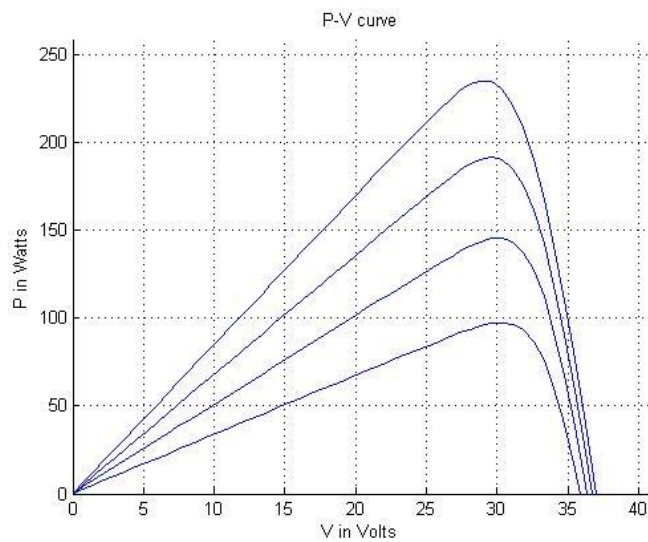


Figure (4.6) *P-V curve of SOLTECH 1STH-235 at different Irradiations*



## CHAPTER 5

### CONCLUSIONS

After going through both the methods for determining unknown parameters, we can conclude the advantages and disadvantages of both over one another.

#### **For 1<sup>st</sup> method**

##### *Advantages*

Since, we assume the value of diode ideality factor beforehand, only two parameters remain unknown. These can be easily determined using Newton method to solve a non-linear equation. No experimental data is required.

##### *Disadvantages*

A big compromise is done by assuming diode ideality factor beforehand. The parameters obtained can be less accurate. Though the computational time is less w.r.t. to other method the number of iterations is large.

#### **For 2<sup>nd</sup> method**

##### *Advantages*

No compromise with any parameter is done. Accuracy is more than the previous method. Though computational time is more, the equations converge in 4 to 10 iterations.

##### *Disadvantages*

Initial values should be properly determined otherwise there is greater number of chances for divergence to take place. Therefore, proper experimental values are required.

## BIBLIOGRAPHY

- [1] A. S. Sedra and K. C. Smith, *Microelectronic Circuits*. London, U.K.: Oxford Univ. Press, 2006.
- [2] H. J. Møller, *Semiconductors for Solar Cells*. Norwood, MA: Artech House, 1993.
- [11] *IEEE Standard Definitions of Terms for Solar Cells*, 1969.
- [12] W. Xiao, W. G. Dunford, and A. Capel, "A novel modeling method for photovoltaic cells," in *Proc. IEEE 35th Annu. Power Electron. Spec. Conf. (PESC)*, 2004, vol. 3, pp. 1950–1956.
- [18] Marcelo Gradella Villalva, Jonas Rafael Gazoli and Ernesto Ruppert Filho "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", *IEEE Transaction on Power Electronics*, Vol. 24, No. 5, Pg.1198-1204, May 2009
- [20] C. Carrero, J. Amador, and S. Arnaltes, "A single procedure for helping PV designers to select silicon PV module and evaluate the loss resistances," *Renewable Energy*, vol. 32, no. 15, pp. 2579–2589, Dec. 2007.
- [21] Gwinyai Dzimano, B.S. "Modeling of Photovoltaic Systems", The Ohio State University, Pg.1-18,48-52, 2008.
- [22] Ryan C. Campbell, A Circuit-based Photovoltaic Array Model for Power System Studies, Pg.1 *Student Member, IEEE*.
- [23] W. De Soto, S.A. Klein, and W. A. Beckman, "Improvement and validation of a model for photovoltaic array performance," *Solar Energy*, vol. 80, no. 1, pp. 78–88, Jan. 2006.
- [24] G. Walker, "Evaluating MPPT converter topologies using a matlab PV model," *J. Elect. Electron. Eng., Australia*, vol. 21, no. 1, pp. 45–55, 2001.
- [25] Daniel S.H. Chan, member IEEE and Jacob C.H. Phang, member IEEE, "Analytical Methods for the Extraction of Solar-Cell Single- and Double-Diode Model Parameters from  $I$ - $V$  Characteristics", *IEEE transactions on electron devices*, Vol. ED-34 No.2 February 1987.
- [A] <http://en.wikipedia.org/wiki/Photovoltaics>

- [B][http://en.wikipedia.org/wiki/Microcrystalline\\_silicon](http://en.wikipedia.org/wiki/Microcrystalline_silicon)
- [C][http://en.wikipedia.org/wiki/Cadmium\\_telluride](http://en.wikipedia.org/wiki/Cadmium_telluride)
- [D][http://en.wikipedia.org/wiki/Copper\\_indium\\_selenide](http://en.wikipedia.org/wiki/Copper_indium_selenide)
- [E]Nielsen, R. 2005, 'Solar Radiation', <http://home.iprimus.com.au/nielsens/>.
- [E]<http://express.howstuffworks.com/gif/solar-power-diagram.jpg>
- [F]<http://science.howstuffworks.com/solar-cell1.htm>
- [G]<http://www.pvresources.com/en/module.php>
- [H][http://www.japanfs.org/ja/files/Stand-Alone\\_PV\\_Modules.jpg](http://www.japanfs.org/ja/files/Stand-Alone_PV_Modules.jpg)
- [I] <http://www.autospectator.com/cars/files/images/Photovoltaic-Cell.jpg>
- [J] [http://en.wikipedia.org/wiki/Photovoltaic\\_array](http://en.wikipedia.org/wiki/Photovoltaic_array)
- [K] [http://www.iaei.org/magazine/wp-content/uploads/2009/05/07ewiles\\_ph4\\_167979301.jpg](http://www.iaei.org/magazine/wp-content/uploads/2009/05/07ewiles_ph4_167979301.jpg)
- [L][http://www.ncsc.ncsu.edu/include/\\_upload/media/pubs/PVApplication.pdf](http://www.ncsc.ncsu.edu/include/_upload/media/pubs/PVApplication.pdf)
- [M] <http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells>
- [19] <http://www.earthscan.co.uk/Portals/0/Files/Sample%20Chapters/9781844074426.pdf>